Compliant Task-Space Control with Back-Drivable Servo Actuators

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Abstract. In this paper, we propose a new approach to compliant task-space control for high degree-of-freedom manipulators driven by position-controlled actuators. The actuators in our approach are back-drivable and allow to limit the torque used for position control. Traditional approaches frequently achieve compliance through redundancy resolution. Our approach not only allows to adjust compliance in the null-space of the motion but also in the individual dimensions in task-space. From differential inverse kinematics we derive torque limits for each joint by examining the contribution of the joints to the task-space motion. We evaluate our approach in experiments with specific motions. We also report on the application of our approach at RoboCup 2010, where we successfully opened and closed the fridge in the RoboCup@Home finals.

Keywords: compliance control, task-space control, domestic service robots, servo actuators.

1 Introduction

In todays industrial settings, robots require fast, precise, and reliable execution of motions. The use of high-stiffness motion control can guarantee robust operation in this domain, but it also demands precise models of the dynamics of the robot mechanism and manipulated objects. Furthermore, precautions need to be taken to prevent physical interaction with humans under any circumstances. However, this approach is not applicable to domains, such as service robotics, in which the environment is less structured, i.e., uncertainty is involved in the models, or physical interaction with humans can not be avoided.

Compliance in motion control opens up new application domains for manipulation robots. Since small errors in model acquisition and estimation can be compensated through compliant control, the robot is able to operate despite measurement errors. It is also possible to use compliant motion for explorative manipulation of objects, especially of articulated objects. Finally, compliant motion allows for direct but safe physical interaction with humans, for example, for teaching by guidance or for physical intervention by humans.

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Fig. 1. Our domestic service robot Dynamaid opens and closes the fridge at RoboCup 2010 in Singapore

For compliant motion control, only the torque necessary to achieve a position, velocity, or force is exerted through the robot actuators. In combination with a light-weight robot construction, this control approach can achieve inherently safe motion, since small forces and torques are required for control. When the desired motion of the robot to achieve a task does not constrain all degrees of freedom of a robot mechanism, redundancy needs to be resolved. The robot may be controlled fully compliant in the null-space of the task-constrained motion.

In this paper, we propose compliant task-space control for redundant manipulators driven by servo actuators. The actuators in our approach are back-drivable and allow to configure the maximum torque used for position control. From differential inverse kinematics we derive a method to limit the torque of the joints depending on how much they contribute to the achievement of the motion in task-space. Furthermore, our approach not only allows to adjust compliance in the null-space of the motion but also in the individual dimensions in task-space. This is very useful when only specific dimensions in task-space shall be controlled in a compliant way. We evaluate our approach quantitatively in experiments for specific task-space motions. We also report on the use of compliant task-space motion control for manipulating articulated objects at RoboCup, where we successfully applied our approach to open and close the fridge in the RoboCup@Home finals 2010 in Singapore (s. Fig. 1).

The remainder of the paper develops as follows. After a brief overview of related work in the fields of compliant and task-space motion control in the next section, we will state our method in Sec. 3. In Sec. 4 we give further insights into our method with an example application. We finally report on the experimental evaluation of our approach in Sec. 5.

2 Related Work

Task-space motion control, initially developed by Liegeois [5], is a well established concept in robotics (s. [6] for a survey). Common to task-space control methods is to transfer motion in a space relevant to a task to joint-space motion. One simple example of task-space control is the control of the end-effector of a serial kinematic chain along pose trajectories in Cartesian space. The task-space control formalism allows to consider secondary objectives, when the task-space motion constrains less degrees of freedom than available in the robot mechanism. Optimization criteria are then projected into the null-space of the motion in joint-space. De Lasa et al. [4], for example, demonstrate how to incorporate multiple secondary objectives consistently into the task-space control framework.

Early approaches to task-space control have been velocity-based [5]. In these methods, velocity-based control laws are derived by differentiation and inversion of a function that maps joint-space configurations to task-space. Acceleration-based [1] and force-based [3] methods have also been proposed. They require precise modelling of the robot dynamics and have been shown to be difficult to implement [6].

For compliant motion control in task-space, acceleration- and force-based methods are naturally suited. Velocity-based methods have been reported to be ill-suited for compliant control, when compliance is established with redundant degrees of freedom of the robot kinematics [6]. Instead of relying on redundancy resolution for compliant control, we propose to adjust compliance for each dimension and direction in task-space as well as in the null-space of the motion when the robot kinematics is redundant for the task.

3 Compliant Task-Space Control with Position-Controlled Actuators

In our method, we employ velocity-based task-space control and derive a control law for compliant motion. We assume that the robot actuators follow position trajectories with servo control loops and that the torque used for control is limitable.

3.1 Velocity-Based Task-Space Controller

Central to task-space controllers is a mapping f from joint states $q \in \mathbb{R}^m$ to states $x \in \mathbb{R}^n$ in task-space, i.e., the forward kinematics

$$x = f(q). \tag{1}$$

By linearization, one obtains the differential relationship

$$\dot{x} \approx J(q)\dot{q} \tag{2}$$

between velocities in joint-space and task-space. The inversion of this relationship yields a mapping from task-space velocities to joint-space velocities,

$$\dot{q} \approx J^{\dagger} \dot{x}, \tag{3}$$

where $J^{\dagger} := J^{\dagger}(q)$ is the pseudo-inverse of $J(q)$. When the task-space has less dimensions than degrees of freedom are available in the robot kinematics, the inverse mapping has a null-space,

$$\dot{q} \approx J^{\dagger} \dot{x} + \left(I - J^{\dagger} J\right) \dot{q}^{0}, \tag{4}$$

in which joint motion $\dot{q}^{0}$ can be projected such that the tracking behavior in task-space is not altered. In this case, we call the robot kinematics redundant for the task.

Given a desired trajectory in task-space $x_d(t)$, we derive a control scheme to follow the trajectory with a position-controlled servo actuator,

$$\begin{aligned} \dot{x}(t) &= K_x \left(x_d(t) - x(t)\right), \text{ and} \\ \dot{q}(t) &= K_q \left(J^{\dagger} \dot{x}(t) + \alpha \left(I - J^{\dagger} J\right) \nabla g(q(t))\right), \end{aligned} \tag{5}$$

where K_x and K_q are gain matrices which can be adjusted in each time step to limit velocities in task- and joint-space, respectively. The cost function $g(q(t))$ optimizes secondary criteria in the null-space of the motion, and α is a step-size parameter. Cost criteria typically cover joint limit avoidance or the preference of a convenient joint state.

3.2 Compliant Task-Space Control

The control loop in each servo actuator implements torque control to achieve a target position in joint-space. In our approach, we assume that the torque applied by the actuator can be limited. We derive the responsibility of each joint for the motion in task-space, and distribute a desired maximum torque onto the involved joints according to their responsibility.

We measure the responsibility of each joint for the task-space motion through the inverse of the Jacobian

$$R_{task}(t) := \text{abs} \left[J^{\dagger}(q(t)) \begin{pmatrix} \Delta x_1 & 0 & \cdots & 0 \\ 0 & \Delta x_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \Delta x_n \end{pmatrix} \right], \tag{6}$$

where $\Delta x := K_x \left(x_d(t) - x(t)\right)$ is the target motion in task-space and abs determines absolute values of a matrix element-wise. Each entry (i, j) of the matrix $R_{task}(t)$ measures the contribution of the velocity of the j-th task component to the velocity of joint i.

In addition, we also define the responsibility of each joint for the null-space motion

$$R_0(t) := \text{abs}\left[\alpha\,(I - J^\dagger J)\,\nabla g(q(t))\right]. \tag{7}$$

Finally, we obtain the responsibility $R(t) := (R_{task}(t), R_0(t))$ of task-space and null-space motion through concatenation of the individual responsibilities.

We determine the compliance $c \in [0,1]^n$ in dependency of the deviation $d_i := x_d(t) - x(t)$ of the actual state $x(t)$ from the target state $x_d(t)$ in task-space, i.e.,

$$c_i := \begin{cases} 1 - \frac{d_i - d^-}{d^+ - d^-} & \text{, if } d^- \leq d_i \leq d^+ \\ 1 & \text{, if } d_i < d^- \\ 0 & \text{, if } d_i > d^+ \end{cases} \tag{8}$$

such that the compliance is one for $d_i \leq d^-$ and d^+ and zero for $d_i \geq d^+$.

For each task dimension i the motion can be set compliant in the positive and the negative direction seperately. The direction of motion is given by the deviation of the actual state in task-space from the target. When the task dimension is not set compliant, we choose high holding torque τ_i^x in this dimension. If it is set compliant, the holding torque

$$\tau_i^x = c_i\,\tau_i^{x-} + (1 - c_i)\,\tau_i^{x+} \tag{9}$$

interpolates between a minimal holding torque τ_i^{x-} for full compliance $c_i = 1$ and a maximal holding torque τ_i^{x+} for minimal compliance $c_i = 0$. The minimal and maximal holding torques should be chosen for the task at hand. For example, when the motion is set compliant along the vertical axis, gravity can be compensated by sufficient minimal holding torque. The holding torque for the null-space motion can also be set to the desired compliance.

We distribute the torques for the individual task dimensions on the joints responsible for the motion in these dimensions. First, we determine the activation matrix

$$A(t) := R(t) \begin{pmatrix} \left(\sum_j R_{j,1}\right)^{-1} & 0 & \cdots & 0 \\ 0 & \left(\sum_j R_{j,2}\right)^{-1} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \left(\sum_j R_{j,n}\right)^{-1} \end{pmatrix}, \tag{10}$$

by normalizing the responsibility of the joints to sum to one along each task dimension. The task component torques are then distributed according to the activation of each joint

$$\tau^q = A(t)\,\tau^x \tag{11}$$

to the individual joint torque limits τ^q.

In order to obtain the responsibility matrix, we linearize the relationship between task- and joint-space at the actual joint positions and incorporate the

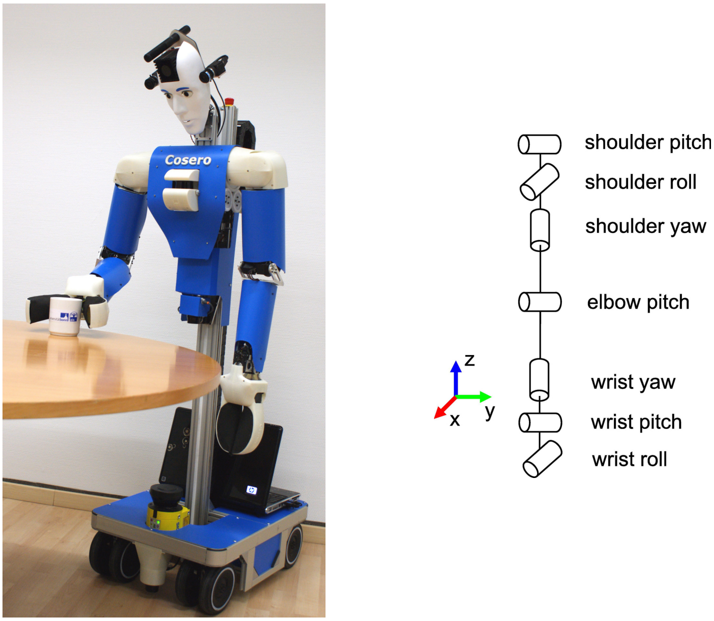

Fig. 2. Left: Cognitive Service Robot Cosero. Right: Schematics of the seven degrees of freedom in the anthropomorphic arms.

deviation of the actual state from the target state in task-space. When large deviations shall be allowed, the linear approximation is coarse and leads to large deviations in uncompliant task dimensions. Instead, we propose to adapt an intermediate target $\tilde{x}_d(t)$ in task-space which complies towards the actual state $x(t)$

$$\tilde{x}_d(t) := x_d(t) + \eta \, (x(t) - x_d(t)), \tag{12}$$

where $\eta \in [0, 1)$ is adjustable. For $\eta \to 1$ the intermediate target fully follows external influences in the compliant task dimensions. Intermediate values of η also control how fast the robot returns to the actual target.

4 Example Application

We exemplify our approach with the mobile manipulation of door leaves by our domestic service robot Cosero. The robot is shown in Fig. 2 together with a schematics of the kinematic model of the 7-DOF anthropomorphic arms of the robot. Cosero's joints are mainly driven by Robotis Dynamixel EX-106+ (10.7 Nm holding torque, 154 g) and RX-64 (6.4 Nm holding torque, 116 g) actuators.

Several approaches exist to manipulate doors when no precise articulation model is known. For instance, Niemeyer and Slotine [7] propose to follow the motion of the door handle using force control. Jain and Kemp [2] use compliant

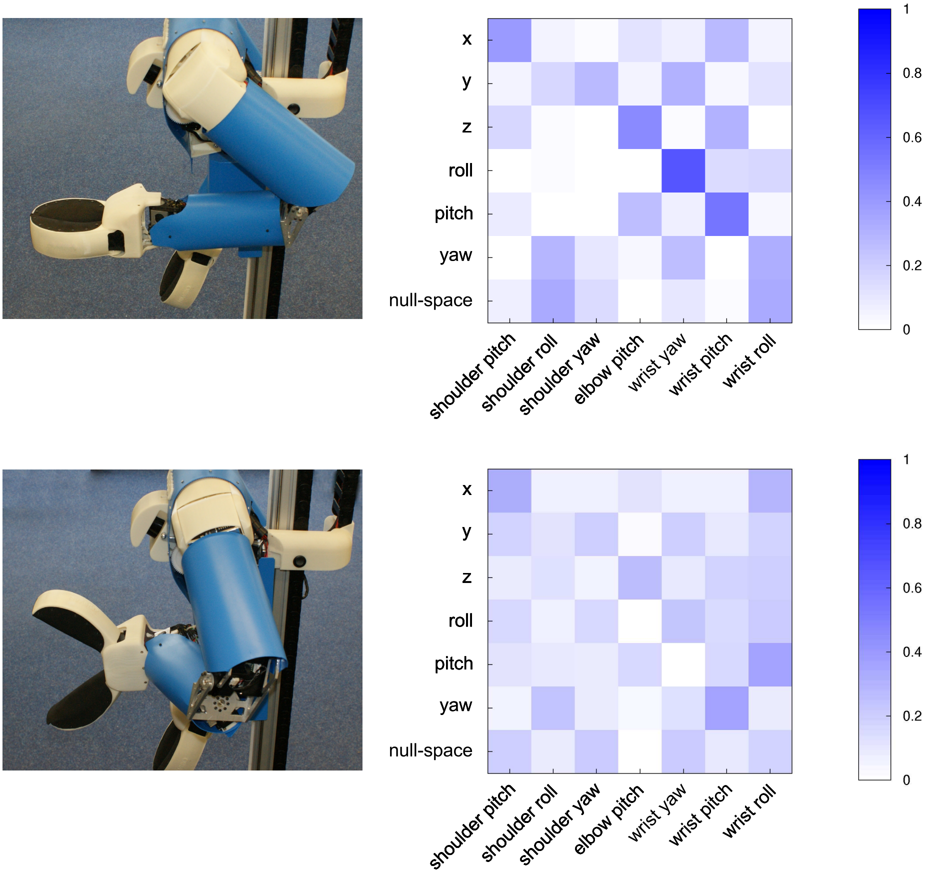

Fig. 3. Examples of activation matrices for two arm poses. The task-space dimensions correspond to forward/backward (x), lateral (y), vertical (z), and rotations around the x-axis (roll), y-axis (pitch), and z-axis (yaw).

equilibrium point control to push a door open. They use force sensors to decide, when the controller fails to grasp the handle or when the door is blocked. Schmid et al. [8] design a controller to adjust the gripper position and orientation in a fixed pose towards the door leaf. They measure deviations from the intended end-effector pose using force and tactile feedback. Our approach does not require feedback from force or tactile sensors.

In order to open the door, the robot grasps the door handle and exerts a force in backward direction, orthogonal to the closed door leaf. We set the motion of the end-effector compliant in the lateral direction and in rotation around the vertical axis, such that the end-effector may comply to the motion of the door handle, which is constrained on a circle by the rotational joint in the door hinge. The robot moves back, until the door handle has reached its maximal position in backward direction and resists further motion. The robot closes the

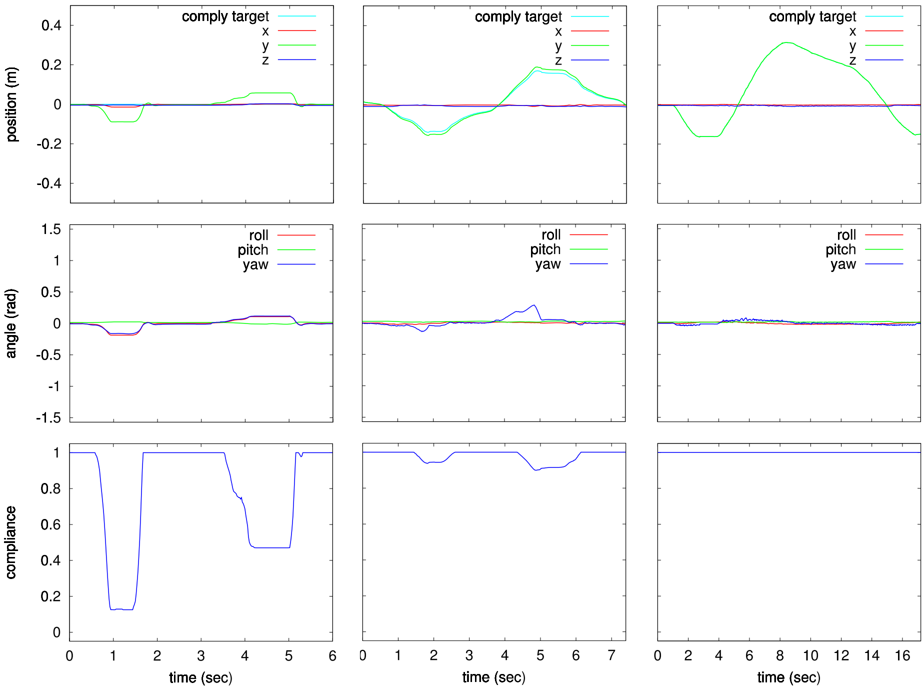

Fig. 4. Deviations from targets in task-space and compliance c for compliant control in y-direction in the vertical grasp pose without target adaptation ($\eta = 0$, left), with intermediate target adaptation ($\eta = 0.9$, center), and with strong target adaptation ($\eta = 0.999$, right)

door by grasping the door handle and exerting a force in forward direction, while following and turning to keep the door handle at the initial grasp position relative to the robot. It pushes the door until the door is closed and resists further forward motion of the end-effector.

In both control applications, the end-effector must comply to the constrained motion of the door handle in specific directions in the task-space, while keeping other directions at their targets. In Fig. 3, we give examples for the activation matrix $A(t)$ in two grasping poses for a door handle. The upper row shows the configuration of the joints and the activation matrix, when the end-effector grasps a vertically aligned door-handle. The grasp in the lower row is aligned to horizontal door handles. The task-space dimensions correspond to forward/backward (x), lateral (y), vertical (z), and rotations around the x-axis (roll), y-axis (pitch), and z-axis (yaw).

It can be seen from the activation matrices, that for both poses, motion in x-direction in task-space involves the elbow and shoulder pitch actuators. For the vertical grasp (upper row), the wrist pitch joint also contributes to the motion in x-direction. In constrast the wrist roll joint contributes to the x-direction for the

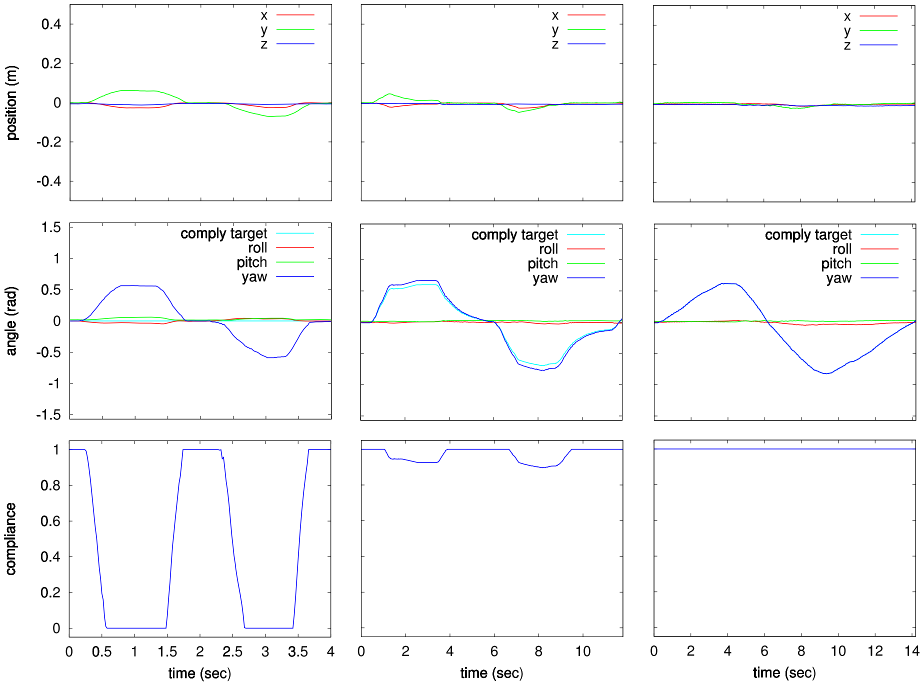

Fig. 5. Deviations from targets in task-space and compliance c for compliant control in yaw-direction in the vertical grasp pose without target adaptation ($\eta = 0$, left), with intermediate target adaptation ($\eta = 0.9$, center), and with strong target adaptation ($\eta = 0.999$, right)

horizontal grasp (lower row). Also, other shoulder and wrist joints add smaller contributions to the motion.

In task-space y-direction, the shoulder roll and yaw joints and the wrist yaw joints are primarily responsible for the motion when grasping vertically. For the horizontal grasp, all joints but the elbow pitch joint contribute significantly to the motion.

For the rotational motion in task-space, we observe, that yaw-rotation strongly involves the shoulder roll, wrist yaw, and wrist roll joints. This is due to the fact, that for a yaw rotation of the end-effector, the shoulder roll joint has to move the elbow in- and outwards, which also induces a roll rotation of the end-effector that is compensated by the wrist roll joint. In vertical grasping alignment, the yaw-rotation is achieved primarily with the shoulder roll and the wrist pitch joint.

5 Experiments

We evaluate the performance of our approach for compliance control with our domestic service robot Cosero (s. Fig. 2). Throughout the experiments we use

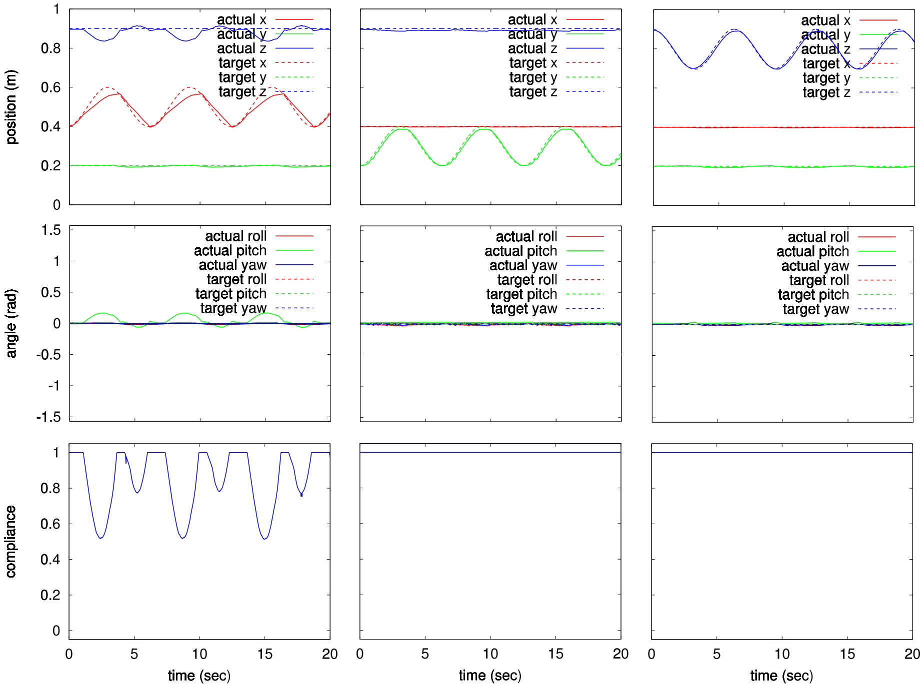

Fig. 6. Tracking performance for sinusoid motion in compliant task-space dimensions (left: x, center: y, right: z)

the settings $d^- = 0.01\,\mathrm{m}$ and $d^+ = 0.1\,\mathrm{m}$ in x-, y-, and z-direction. In the roll-, pitch-, and yaw-directions we choose $d^- = 0.04\,\mathrm{rad}$ and $d^+ = 0.4\,\mathrm{rad}$.

5.1 Compliance Control in Static Poses

In a first set of experiments, we set the motion compliant in y-direction, while the target pose is kept constant at the vertical grasp pose (s. Fig. 3, top left). Fig. 4 shows the reaction of our controller on applied forces in lateral directions on the wrist for different settings of the target adaptation rate η. When the adaptation rate is set to $\eta = 0$, the end-effector complies only by a fraction of d^+. Compliance decreases with deviation and the limit torques increase until the arm resists further motion in y-direction. Since the target is not adapted to the actual pose of the end-effector, other task dimensions also deviate from their target position. As soon as the applied force ceases, the end-effector moves back to its target pose. At an adaptation rate of $\eta = 0.9$, the end-effector may comply farer to the external force, while motion in other task dimensions is reduced. When the applied force is suddenly reduced to zero, the end-effector slowly moves back to its target pose. For $\eta = 0.999$, the end-effector fully complies to the applied force, while other task dimensions can be controlled close at their

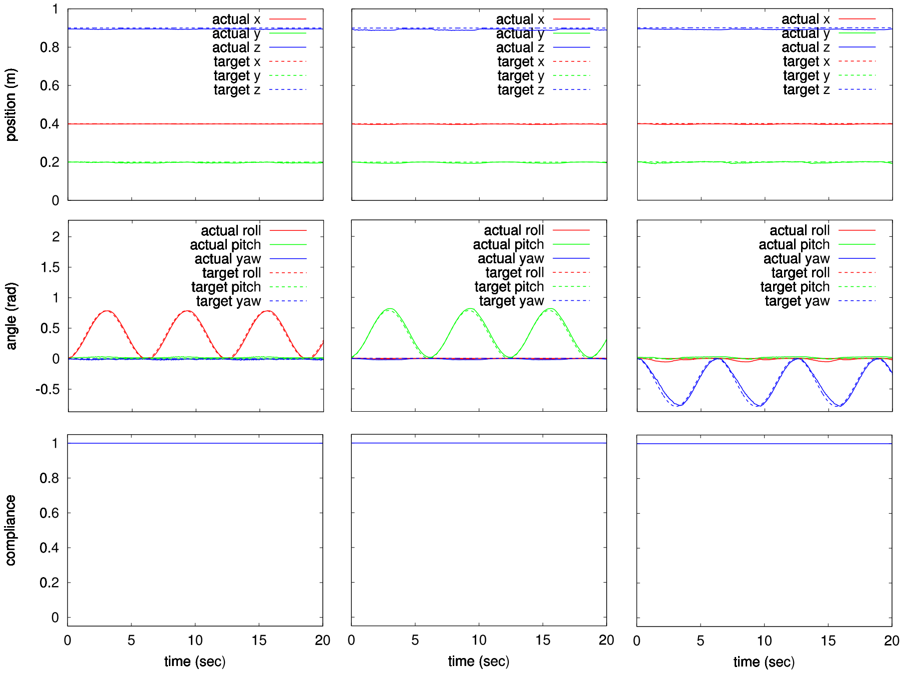

Fig. 7. Tracking performance for sinusoid motion in compliant task-space dimensions (left: roll, center: pitch, right: yaw)

target positions. Since gravity always acts on the robot arm, the end-effector moves to an equilibrium pose when the applied force is removed.

We also evaluate our controller for different settings of the target adaptation rate η in the yaw-direction. On the end-effector we apply torques in yaw direction. From Fig. 5 it can be seen that the controller behaves similarly to applied torques in yaw-directions like in the experiments with forces in the compliant y-direction.

5.2 Tracking with Compliance Control

We further evaluate the tracking behavior of our approach without target adaptation, i.e. $\eta = 0$. We set each each task dimension compliant individually and examine the tracking of a sinusoid target motion in the compliant task dimension. For the y-, z-, roll-, pitch-, and yaw-direction, the controller follows the target motion very well.

In the x-direction, the controller temporarily looses track in the z-dimension in downwards direction when the arm extends far forward. This is due to the fact that the pitch joints are concurrently involved in the motion in x-direction as well as in z-direction. Since the deviation in z-direction also leads to a tracking error in x-direction, compliance in x decreases. By this, the available torque in the pitch joints increases until the deviation in z-direction can be corrected.

6 Conclusions

In this paper we proposed an approach to redundant task-space control that allows for compliance control in individual directions of the task-space. Our approach extends velocity-based task-space control and is suited for back-drivable position-controlled actuators for which the available torque can be limited.

From differential inverse kinematics, we derive a controller that distributes torque limits for compliant directions in task-space onto the joints that are responsible for the motion. The controller allows to adjust the compliance range in task-space and the rate with which it adapts its target to follow external forces.

In experiments we show that our controller achieves the desired compliance behavior when it holds a static pose. We evaluated the controller for different target adaptation rates. We also demonstrated that the controller is capable to track motion in compliant task-space dimensions. Finally, at RoboCup 2010 in Singapore, we successfully applied our approach to open and close the fridge in the finals of the RoboCup@Home league. The performance of the robot was well received by the jury.

Our approach is easy to implement when a velocity-based controller is available. In future work, we could improve the distribution of forces and torques in task-space onto the joints by considering the dynamics of the robot mechanism.

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